

NBS REPORT

8837

EIGHTEENTH PROGRESS REPORT

to

National Aeronautics and Space Administration

on

Cryogenic Research and Development

for

Period Ending June 30, 1965



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NATIONAL BUREAU OF STANDARDS

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		NERVA Program	
		M-1 Program	
			*Continuing Effort
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FLUIDS PROPERTIES											
1	Viscosity, p-H ₂										
2	Sonic Velocity, p-H ₂										
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Apparatus Designing					
Preliminary Planning					
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Item Number		1	2	3	4

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1. Physical Properties of Cryogenic Fluids

R. D. Goodwin, H. M. Roder, L. A. Weber, and B. A. Younglove

1.1 Parahydrogen

Publications on viscosity by D. E. Diller, and on sonic velocity by B. A. Younglove are listed below. Notes by R. J. Corruccini on refractive index and on surface tension are in press as listed below. The final compilation of thermodynamic properties by Roder and Weber is in press for an NBS monograph, listed below.

Work on the equation of state has taken a favorable turn, resulting from use of the Beattie-Bridgeman form for density-dependence of the internal pressure (R. D. G.).

Experimental work has begun on apparatus for determining dielectric constant of the solid (B. A. Younglove), and for thermal conductivity of fluid (H. M. Roder and Gary Petersen). Experimental work is contemplated on refractive index.

"Tabcode" is the reduction of hydrogen properties to a high speed computer program. This program may be used like a "black box" to obtain hydrogen properties at pressures from 1 to 5000 psia, and temperatures from the triple point, 24.845°R, to 5000°R. Included here are the listings of two of these programs as written and running on a Control Data Corporation 3600 computer.

Although these programs are written in "Fortran," certain changes are necessary to make them compatible to IBM equipment. These changes are:

1. Change all DATA statements from CDC form to IBM form, e.g. DATA (R = 1.0) to DATA R/1.0/.

2. Eliminate all double replacement statements, e.g.

$$I = PR = P/587.84 \text{ to } PR = P/587.84$$

$$I = PR$$
3. Insert the implied conversions from fixed to floating point to all mixed mode arithmetic expressions, e.g.

$$F = PR - I \text{ to } F = PR - \text{FLOAT}(I).$$

The first program listed, PHTEMP, returns a temperature in °R when it is provided with a pressure, PRES, in psia and an enthalpy, ENTH, in BTU/lb. A typical Fortran statement might be:

$$T = \text{PHTEMP}(14.696, 81.4, \text{QUAL}).$$

This would cause T to be replaced by the temperature corresponding to 1 atmosphere (14.696 psia) and 81.4 BTU/lb. The value of T in this example is the boiling temperature of hydrogen at 1 atmosphere, 36.48°R.

PHTEMP also returns the quality of the fluid, QUAL. The quality is 1.0 for a gas, 0.0 for a liquid and -1.0 for a solid. In the liquid-vapor dome, a number between 0 and 1 is returned for quality which is the ratio:

$$\text{QUAL} = \frac{\text{Mass of Vapor}}{\text{Total Mass}}$$

For values of pressure and enthalpy below the solidus line:

$$\text{QUAL} = -\frac{\text{Mass of Solid}}{\text{Total Mass}}.$$

Whenever requests are below the solidus line, the temperature returned will be the temperature on the solid-liquid boundary. Qualities less than -1.0 mean only that the hydrogen is all solid and no attempt is made to return temperature of solid hydrogen. The temperature will still be the temperature at the solid-liquid boundary.

PH TEMP agrees, to at least 1%, with the source data, which is:

SOURCE	PRESSURE RANGE	ENTHALPY RANGE
	psia	BTU/lb.
NBS Report 7987	1 to 5000	-110 to 425
NBS Tech. Note 130	1 to 1500	425 to 1800
ASD Tech. Report 61-360 (AiResearch Mfg. Co.)	1 to 3000	1800 to 20,000

Values for freezing hydrogen are taken from Goodwin and Roder's paper.*

Requests for values outside the pressure range are extrapolated but should still be fairly accurate since the variation of temperature with pressure is quite linear outside the range of the reference data.

The second program listed, PHENTR, returns an entropy in BTU/lb. -°R for a typical Fortran statement:

$$S = \text{PHENTR} (P, H).$$

The pressure, P, must be in psia, and the enthalpy, H, in BTU/lb. The source data is the same as for PHTEMP, but extrapolation may not be so good from this table since entropy varies as the logarithm of pressure. The error in this case is also held to within 1% of the source data. The same conversion is also needed if the program is to be used on an IBM rather than a CDC computer because of the difference in their respective Fortran systems.

These two programs are operational at the present time and decks are available. Decks for other variables; density, internal energy, specific heat, sound velocity, viscosity, and thermal conductivity; should be available shortly for both pressure-enthalpy and pressure-temperature entries.

*Goodwin, R. D., and Roder, H.M., Pressure-Density-Temperature Relations of Freezing Liquid Parahydrogen to 350 Atmospheres, Cryogenics 3, 12-15 (March 1963).

```

FUNCTION PHTEMP(PRES,ENTH,QUAL)
  DIMENSION LOC(12),JP(12),T(375),DP(12),DH(12),BP(12),BH(12),MX(12)
  1,R(19),TL(19),TG(19),TF(19),SH(10),TS(10)
  DATA (R=1.022,2.0,4.0,8.0,14.0,25.0,43.0,69.0,99.0,128.0,151.0,
1165.0,176.0,182.0,185.0,186.5,187.25,187.46875,187.506), (TG=60.31,
265.11,70.59,76.35,80.98,85.11,87.40,86.54,81.94,74.15,64.83,56.86,
347.34,39.56,33.46,28.34,22.31,18.66,16.55), (TL=-132.8,-129.13,
4-124.25,-117.79,-110.86,-101.3,-89.04,-74.22,-58.58,-43.43,-30.07,
5-20.56,-11.13,-4.27,1.17,5.54,10.83,14.29,16.36), (TF=24.845,27.07,
629.81,33.07,36.18,39.96,44.12,48.33,51.97,54.79,56.72,57.80,58.57,
758.99,59.18,59.29,59.34,59.353,59.356)
  DATA (SH=-132.8,-109.96,-87.59,-65.71,-44.27,-23.18,-2.45,18.06,
138.32,58.50), (TS=24.846,27.175,29.310,31.299,33.176,34.962,36.672,
238.317,39.904,41.456)
  DATA(LOC=7,100,118,150,1,178,218,9,283,331,340,358)
  DATA(JP=11,3,8,7,11,8,13,11,8,3,3,3)
  DATA(MX=0,1,6,5,9,6,11,1,6,1,1,1)
  DATA(DP=3000.0,750.0,587.84,146.96,440.88,587.84,73.48,293.32,
173.48,1500.0,120.0,6.0)
  DATA(DH=3000.0,275.0,85.306,85.306,19.194,31.99,31.99,20.26,19.194
1,5000.0,2000.0,2000.0)
  DATA(BP=0.0,881.76,0,587.84,881.76,0,0,73.48,0,-40.0,-2.0)
  DATA(BH=1800.0,425.0,170.61,170.61,-110.9,42.65,42.65,-134.4,
1-53.32,10000.0,10000.0,10000.0)
  DATA((T(I),I= 1, 99)= 26.93,18.54,10.35, 0, 0, 0,538.3,
1525.8,24.22,18.56,11.13,37.27,29.70,21.66,13.12, 0, 0,1399.,
21379.,34.94,30.37,24.81,45.61,40.12,32.85,24.73,10.16, 0,2235.,
32214.,42.93,40.14,36.22,52.51,48.58,43.00,35.98,28.21,19.23,3017.,
43003.,48.76,47.69,45.19,58.36,55.84,51.48,45.90,39.12,31.21,23.56,
5 0,52.66,53.63,52.51,63.38,62.26,58.95,54.38,48.80,42.25,34.65,
627.13,19.19, 0, 0,67.70,68.04,65.68,61.94,57.24,51.72,45.36,
738.02,30.67,23.10, 0,71.50,73.35,71.91,68.91,64.87,60.10,54.65,
848.49,41.47,33.99,26.07,74.93,78.30,77.75,75.40,71.97,67.79,62.98,
957.60,51.59,44.88,37.44)
  DATA((T(I),I=100,117)= 165.5,176.5,180.2,245.1,248.6,250.0,316.1,
1317.2,316.9,387.5,387.1,385.7,461.7,460.1,457.8,538.3,535.9,532.9)
  DATA((T(I),I=118,149)= 106.4,112.0,112.8,111.2,108.2,104.2,99.50,
194.30,128.7,134.5,136.4,135.9,134.0,131.2,127.7,123.6,152.8,157.6,
2159.5,159.5,158.2,156.0,153.3,150.0,177.0,180.5,182.0,182.0,181.1,
3179.2,176.9,174.1)
  DATA((T(I),I=150,177)= 69.28,80.43,88.86,95.21,99.97,103.6,106.4,
1103.7,110.0,115.2,119.6,123.2,126.2,128.7,136.4,140.2,143.5,146.4,
2148.9,151.0,152.8,166.0,168.5,170.7,172.6,174.3,175.7,177.0)
  DATA((T(I),I=178,217)= 77.80,77.75,74.35,69.24,62.98,55.67,47.21,
137.67,84.89,86.83,84.76,80.75,75.55,69.44,62.53,54.74,91.80,95.41,
294.51,91.44,87.08,81.83,75.86,69.24,98.89,103.7,103.8,101.5,97.90,
393.33,88.07,82.24,106.4,112.0,112.8,111.2,108.2,104.2,99.50,94.30)
  DATA((T(I),I=218,282)= 17.02,50.26,55.60,62.01,66.36,69.49,71.82,
173.58,74.93,75.97,76.77,77.40,77.80,30.60,46.62,57.11,64.14,69.25,
273.12,76.12,78.50,80.39,81.90,83.13,84.12,84.89,43.29,54.15,62.43,
368.86,73.91,77.95,81.22,83.90,86.11,87.94,89.47,90.76,91.80,56.29,
464.12,70.62,76.07,80.62,84.38,87.59,90.31,92.61,94.57,96.25,97.67,
598.89,69.28,75.23,80.43,84.94,88.86,92.26,95.21,97.77,99.97,101.9,
6103.6,105.1,106.4)
  DATA((T(I),I=283,330)= 52.78,53.28,53.56,53.62,53.51,53.28,52.93,
152.50,56.63,56.25,57.33,57.97,58.34,58.50,58.50,58.35,59.99,57.71,

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259.72,61.20,62.13,62.78,63.18,63.37,    0,57.51,60.91,63.37,65.10,
366.27,67.12,67.69,    0,56.68,61.52,65.01,67.46,69.21,70.52,71.49,
4    0,56.25,62.01,66.36,69.49,71.82,73.47,74.93)
DATA((T(I),I=331,339)=2816.0,2807.0,2797.0,4044.0,4044.0,4037.0,
15039.0,5118.0,5139.0)
DATA((T(I),I=340,357)=2817.,2816.,2815.,3317.,3323.,3323.,3765.,
13802.,3807.,4124.,4236.,4256.,4390.,4610.,4656.,4587.,4921.,5001.)
DATA((T(I),I=358,375)=2813.,2817.,2817.,3294.,3314.,3319.,3663.,
13753.,3775.,3908.,4104.,4155.,4079.,4369.,4455.,4209.,4575.,4692.)
P=PRES
H=ENTH
Q=1.0
IF(H.LT.42.65) GO TO 10
IF(H.GE.170.61) GO TO 1
N=6
GO TO 2
1 IF(H.GE.426.53) GO TO 3
N=3
2 IF(P.LT.881.76) N=N+1
GO TO 15
3 IF(H.GE.1800.0) GO TO 4
N=2
GO TO 20
4 IF(H.GE.10800.0) GO TO 5
N=1
GO TO 20
5 IF(P.LE.200.0) GO TO 6
N=10
GO TO 20
6 IF(P.LE.11.0) GO TO 7
N=11
GO TO 20
7 N=12
GO TO 20
10 IF(P.LT.587.84) GO TO 11
N=5
GO TO 15
11 IF(H.GE.-53.32) GO TO 12
N=8
GO TO 15
12 N=9
15 IF(H.GT.87.55) GO TO 20
I=PR=P/587.84
IF(I.GT.8) I=8
F=PR-I
FP=1.0-F
HS=FP*SH(I+1)+F*SH(I+2)
TQ=FP*TS(I+1)+F*TS(I+2)
IF(H.LT.HS) GO TO 17
IF(P.GT.187.506) GO TO 20
IF(P.LT.1.021) GO TO 105
DO 104 I=2,19
IF(P-R(I))102,101,104
101 HL=TL(I)
HG=TG(I)
TQ=TF(I)

```

```

      GO TO 106
102  D=R(I)-R(I-1)
      PRR=R(I)-P
      PPR=P-R(I-1)
      HL=(TL(I)*PPR+TL(I-1)*PRR)/D
      HG=(TG(I)*PPR+TG(I-1)*PRR)/D
      TQ=(TF(I)*PPR+TF(I-1)*PRR)/D
      GO TO 106
104  CONTINUE
105  HL=-132.8
      HG=60.31
      TQ=24.84
106  IF (H.GT.HL) GO TO 16
      Q=0.0
      GO TO 20
16   IF (H.GT.HG) GO TO 20
      Q=(H-HL)/(HG-HL)
      GO TO 30
17   Q=(H-HS)/(0.0026806*P+25.021)
      GO TO 30
20   FP=(P-BP(N))/DP(N)
      IP=FP
      IF (IP.GT.MX(N)) IP=MX(N)
      F=FP-IP
      FP=1.0-F
      FH=(H-BH(N))/DH(N)
      IH=FH
      FF=FH-IH
      FH=1.0-FF
      I=IH*JP(N)+IP+LOC(N)
      J=I+JP(N)
      TQ=FP*FH*T(I)+F*FH*T(I+1)+FP*FF*T(J)+F*FF*T(J+1)
30   QUAL=Q
      PHTEMP=TQ
      RETURN
      END

```

```

FUNCTION PHENTR(PRES,ENTH)
  DIMENSION LOC(20),JP(20),S(533),DP(20),DH(20),BP(20),BH(20),MX(20)
  1,R(19),HL(19),HG(19),SL(19),SG(19),HS(10),SS(10),TS(10)
  COMMON/ENTRPy/S
  DATA ((S(I),I=1,16)=6.725,6.142,5.815,5.586,7.631,6.986,6.615,
16.354,8.316,7.648,7.259,6.983,8.871,8.192,7.795,7.513)
  DATA ((S(I),I=17,36)=8.589,7.718,7.284,6.997,6.785,9.576,8.683,
18.230,7.925,7.696,10.286,9.387,8.927,8.618,8.384,10.85,9.949,
29.488,9.175,8.938)
  DATA ((S(I),I=37,56)=10.837,9.938,9.478,9.168,8.933,11.837,10.936,
110.473,10.161,9.925,12.553,11.650,11.188,10.874,10.637,13.118,
212.215,11.753,11.439,11.201)
  DATA ((S(I),I=57,74)=7.698,7.012,6.598,9.014,8.309,7.884,9.993,
19.285,8.859,10.777,10.070,9.645,11.427,10.721,10.300,11.797,11.276
2,10.856)
  DATA (R=1.022,2.0,4.0,8.0,14.0,25.0,43.0,69.0,99.0,128.0,151.0,
1165.0,176.0,182.0,185.0,186.5,187.25,187.46875,187.506)
  DATA (HG=60.31,65.11,70.59,76.35,80.98,85.11,87.40,86.54,81.94,
174.15,64.83,56.86,47.34,39.56,33.46,28.34,22.31,18.66,16.55)
  DATA (HL=-132.8,-129.13,-124.25,-117.79,-110.86,-101.3,-89.04,
1-74.22,-58.58,-43.43,-30.07,-20.56,-11.13,-4.27,1.17,5.54,10.83,
214.29,16.36)
  DATA (SG=8.961,8.508,8.038,7.567,7.190,6.796,6.401,6.022,5.680,
15.375,5.117,4.930,4.742,4.596,4.485,4.397,4.312,4.253,4.195)
  DATA (SL=1.185,1.322,1.491,1.693,1.886,2.126,2.398,2.692,2.974,
13.229,3.444,3.595,3.744,3.858,3.942,4.015,4.089,4.154,4.195)
  DATA (HS=-132.8,-109.96,-87.59,-65.71,-44.27,-23.18,-2.45,18.06,
138.32,58.50)
  DATA (TS=24.845,27.175,29.310,31.299,33.176,34.962,36.672,38.317,
139.904,41.456)
  DATA (SS=1.185,1.207,1.229,1.249,1.267,1.284,1.299,1.315,1.331,
11.347)
  DATA (LOC=309.1,17,37,57,75,99,117,141,157,173,193,217,241,271,
1303,424,454,469,504)
  DATA (JP=11,4,5,5,3,4,3,4,4,4,5,4,4,5,8,11,3,3,7,6)
  DATA (MX=3,2,3,3,1,2,1,2,2,2,3,2,2,3,6,9,1,1,5,4)
  DATA (BP=800.0,150.0,20.0,2.0,500.0,100.0,20.0,0,0,0,-5.0,0,0,-5.0
1,881.76,587.84,0,293.92,0,0)
  DATA (BH=170.0,170.0,170.0,170.0,425.0,425.0,425.0,425.0,2000.0,
12000.0,2000.0,5000.0,5000.0,5000.0,60.0,-110.0,-119.0,42.65,42.65,
242.65)
  DATA (DP=900.,150.,30.,3.,500.,100.,20.,5.,1000.,100.,10.,1000.,
1100.,10.,587.84,440.88,293.92,220.44,29.392,2.9392)
  DATA (DH=85.3,85.3,85.3,85.3,275.0,275.0,275.0,275.0,1000.0,1000.0
1,1000.0,3000.0,3000.0,3000.0,37.0,17.0,18.0,31.99,31.99,31.99)
  P=PRES
  H=ENTH
  IF(H.LE.170.6) GO TO 11
  IF(H.GE.425.9) GO TO 4
  IF(P.LE.700.0) GO TO 1
  N=1
  GO TO 33
1 IF(P.LE.145.0) GO TO 2
  N=2
  GO TO 33
2 IF(P.LE.17.0) GO TO 3

```



```

N=3
GO TO 33
3 N=4
GO TO 33
4 IF(H.GE.1800.0) GO TO 8
  IF(P.LE.450.0) GO TO 5
  N=5
GO TO 33
5 IF(P.LE.70.0) GO TO 6
  N=6
GO TO 33
6 IF(P.LT.18.0) GO TO 7
  N=7
GO TO 33
7 N=8
GO TO 33
8 IF(H.GE.5000.0) GO TO 10
  N=9
9 IF(P.LE.375.0) N=N+1
  IF(P.LE.40.0) N=N+1
GO TO 33
10 N=12
GO TO 9
11 IF(P.LE.800.0) GO TO 13
  IF(H.LE.60.0) GO TO 12
  N=15
GO TO 33
12 N=16
GO TO 27
13 IF(H.GE.43.0) GO TO 14
  IF(P.GE.587.84) GO TO 12
  N=17
GO TO 20
14 IF(P.LE.191.0) GO TO 15
  N=18
GO TO 33
15 IF(P.LE.18.0) GO TO 16
  N=19
GO TO 20
16 N=20
20 IF(P.GT.187.506) GO TO 27
  DO 24 I=2,19
  IF(P-R(I))22,21,24
21 HLIQ=HL(I)
  HGAS=HG(I)
  SLIQ=SL(I)
  SGAS=SG(I)
GO TO 25
22 D=R(I)-R(I-1)
  PRR=R(I)-P
  PPR=P-R(I-1)
  HLIQ=(HL(I)*PPR+HL(I-1)*PRR)/D
  HGAS=(HG(I)*PPR+HG(I-1)*PRR)/D
  SLIQ=(SL(I)*PPR+SL(I-1)*PRR)/D
  SGAS=(SG(I)*PPR+SG(I-1)*PRR)/D
GO TO 25

```

```

24 CONTINUE
25 IF (H.GT.HGAS) GO TO 27
   IF (H.LT.HLIQ) GO TO 27
   PHENTR=(H-HLIQ)/(HGAS-HLIQ)*(SGAS-SLIQ)+SLIQ
   RETURN
27 PR=P/587.84
   I=PR
   IF (I.GT.8) I=8
   F=PR-I
   FP=1.0-F
   HSOL=FP*HS(I+1)+F*HS(I+2)
   IF (H.GT.HSOL) GO TO 33
   PHENTR=FP*SS(I+1)+F*SS(I+2)-(HSOL-H)*(FP*TS(I+1)+F*TS(I+2))
   RETURN
33 FP=(P-BP(N))/DP(N)
   IP=FP
   IF (IP.GT.MX(N)) IP=MX(N)
   F=FP-IP
   FP=1.0-F
   FH=(H-BH(N))/DH(N)
   IH=IH
   FF=FF-IH
   FH=1.0-FF
   I=IH*JP(N)+IP+LOC(N)
   J=I+JP(N)
   PHENTR=FP*FH*S(I)+F*FH*S(I+1)+FP*FF*S(J)+F*FF*S(J+1)
   RETURN
END

```

1.2 Oxygen

The apparatus which was used for PVT determinations on hydrogen has been modified by L. A. Weber. A first set of measurements on oxygen has been correlated and is reported in a Lab Note, listed below. It would be valuable to measure specific heats of oxygen (to check the thermodynamic properties network). This work might be undertaken by D. E. Diller upon his return from a year of academic leave.

1.3 Move to the New Building

During recent months, B. A. Younglove has reconstructed apparatus, cryostats, vacuum systems, and instrumentation used for dielectric constant, viscosity and sonic velocities.

Publications

1. R. B. Stewart and H. M. Roder, Properties of Normal and Para Hydrogen. Chapter 11 in Technology and Uses of Liquid Hydrogen. Scott, Denton, and Nicholls, Editors, Pergamon Press, Inc., New York (1964). [Noted in 16th Progress Report, NBS Report 8728, page 27, item 19.]
2. Dwain E. Diller, Measurements of the Viscosity of Parahydrogen, J. Chem. Phys. 42 (6), 2089-2100 (15 March 1965).
3. H. M. Roder, L. A. Weber, and R. D. Goodwin, Thermodynamic and Related Properties of Parahydrogen from the Triple Point to 100°K at Pressures to 340 Atmospheres, NBS Monograph 94 (in press July 1965).
4. Benny A. Younglove, Speed of Sound in Fluid Parahydrogen, J. Acoustical Soc. Am. Publication due in the September 1965 issue (Experimental measurements, 15 to 100°K, up to 300 atm.).

5. Lloyd A. Weber, Density of Compressed Liquid Oxygen from 88 to 108°K, NBS Cryogenics Division Lab Note No. 65-17, July 1965.
6. R. J. Corruccini, Refractive Index and Dispersion of Liquid Hydrogen, NBS-CD Lab Notes 64-16, 65-4 (in press July 1965 as an NBS Technical Note).
7. R. J. Corruccini, Surface Tensions of Normal and Para Hydrogen, (in press July 1965 as an NBS Technical Note).

2. Cryogenic Metrology (Instrumentation)

2.0 General Comments

Personnel contributing to the activity during this period were: W. J. Alspach, D. A. Burgeson, J. W. Dean, T. M. Flynn, R. J. Richards, and N. C. Winchester.

2.1 Temperature

The following is a report on an analysis of the temperature response of a simple thermometer:

The Instrument Society of America defines time constant as the length of time required for the output of a transducer to rise to 63% of its final value as a result of a step change of measurand. NASA is currently sponsoring cryogenic thermometer research and is using this definition in their specifications. As a result, several private companies and government laboratories are measuring thermometer time constants - each using a slightly different technique. Some are creating step temperature changes by plunging a room temperature thermometer into the cryogen, some precool the thermometer first, while others create the temperature change by withdrawing the thermometer from the cryogen. This note analyzes the problem with the aid of an analog computer.

Mathematical Basis of Time Response

The business of time response is based on the simple mathematics of heat flow into or out of a bolus of material - say a block of copper. The equation is:

$$C \frac{dT}{d\theta} = q, \quad (1)$$

where: C = thermal capacitance of copper block
 T = temperature above liquid boiling temperature
 θ = time
 q = heat transfer rate

The heat transfer rate is then written in terms of the thermal resistance, R , to heat flow and is defined as:

$$R = \frac{T}{q} , \quad (2)$$

combining (1) and (2) results in:

$$RC \frac{dT}{d\theta} = T. \quad (3)$$

The RC term of (3) has the dimensions of time and is called τ . The well known solution of the linear ordinary differential equation (3) to a step temperature change is:

$$T = 1 - e^{-\frac{\theta}{\tau}} . \quad (4)$$

When T has completed 63.2% of its change, θ will equal τ . The time required for this to occur is defined as the time constant. Note that the time constant is independent of the size of the initial temperature change.

Model of Single Mass Thermometer

The simplest mechanically constructed thermometer possible is the thermocouple made by twisting wires of material with different thermoelectric properties together without other constraints. The thermocouple junction best represents the single thermal capacitance block used in equation (1). Platinum resistance thermometers are made of several mechanical components, each with a thermal capacitance; thus equation (1) does not represent this thermometer. A set of equations similar to (1) could be written for each capacitance leading to a high order differential equation, but this approach will not be covered in this note. Germanium, gallium diodes, and other single mass thermometer elements are sufficiently represented by equation (1), except when they are enclosed by a thermometer well or probe.

The heat transfer into the thermometer may be by radiation, conduction down the lead wires, and by convection. The term q , on the right of equation (1) should include these three components. For

simplification, ignore radiation since its contribution will be small and assume that the lead wires are tempered so that no conduction occurs. Thus only convection is left.

The heat transfer by convection is controlled by the equation:

$$q = h A T, \quad (5)$$

where h = convection heat transfer coefficient A = area. By comparing (5) with (2) it may be seen that:

$$R = \frac{1}{h A} . \quad (6)$$

The thermal capacitance may be written in terms of its mass and specific heat. Thus:

$$C = m C_p . \quad (7)$$

Combining (6) and (7) into (3) results in:

$$\frac{m C_p}{A} \frac{dT}{d\theta} = h T. \quad (8)$$

The parameter, $m C_p / A$, is a characterization of the thermometer while the parameter, h , is a characterization of its environment. The parameter, $m C_p / A$, is constant for each thermometer except for the temperature dependency of the specific heat, but the film coefficient depends on the cryogen used as well as the thermometer temperature. In order that equation (4) represent the solution of (8), the film coefficient and specific heat term must be held constant. This is not the case when a thermometer is plunged into a boiling cryogen.

Consider the case of pool boiling in liquid nitrogen. Table I gives values for the boiling film coefficient [1] as a function of the temperature above the normal boiling temperature.

Table I

<u>T</u> <u>°K</u>	<u>h</u> <u>watt/cm² - °K</u>
1	.05
10	.52
40	.05
100	.02
200	.015

These values are an average of many experimental points that vary over an order of magnitude. Table I represents the possible characterization of a pool boiling condition. Thus $h = f(T)$ and equation (8) is a non-linear ordinary differential equation. Equation (8) is also non-linear because $C_p = f(T)$; however, this is not as strong a dependency and will be considered as an average value in the solution that follows.

Analog Model

Equation (8) has been solved on our REAC analog computer. Assuming that the liquid nitrogen is boiling at 78°K and that the original thermometer temperature is 300°K, then the maximum T is 300-78°K or 222°K. The maximum value of h of 1 watt/cm² - °K was used. The magnitude scaling is shown in Table II.

Table II

<u>Variable</u>	<u>Max. Value</u>	<u>Scale Factor</u>	<u>Scaled Variable</u>
T	200°K	100/222 volts/°K	[.45T]
\dot{T}	scaled same as T		[.45T]
h	1 w/cm ² - °K	100/1 watt/cm ² - °K volt	[100 h]

Some approximate values needed to determine the coefficient of equation (8) are:

$$m = .5 \text{ grams}$$

$$C_p = .4 \text{ watt-sec/gr-}^\circ\text{K}$$

$$A = 1 \text{ cm}^2$$

From the above it may be calculated that a typical value of $m C_p / K$ is $.2 \text{ watt-sec/cm}^2\text{-}^\circ\text{K}$. Thus the scaled equation is:

$$[.45 \dot{T}] = \frac{5}{100} [100h] [.45 T].$$

The hundred term in the denominator comes from the use of the multiplier. The analog flow diagram is shown in Fig. 1.

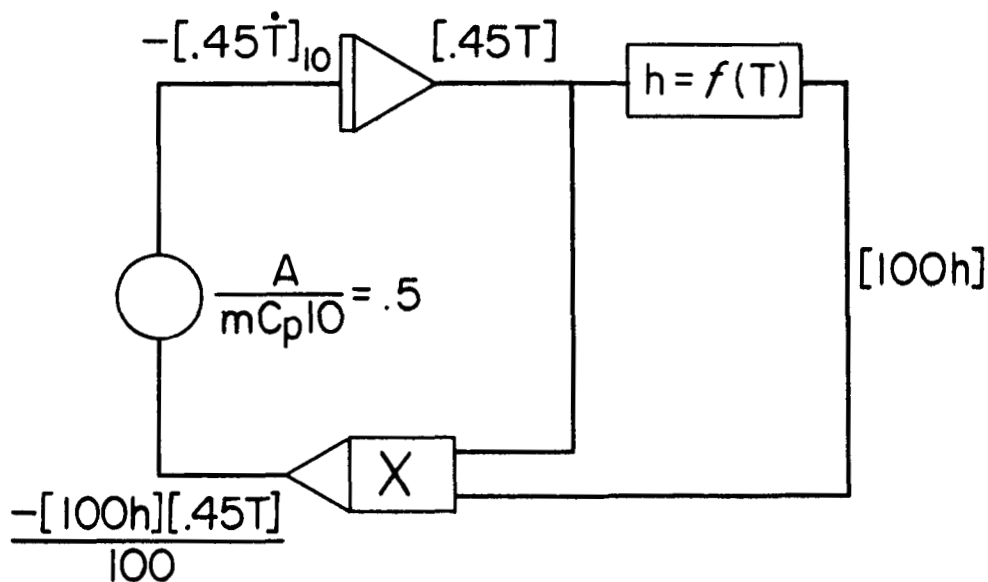


Fig. 1

The problem was run for values of $m C_p / A$ ranging from .1 to 1.0 to cover a wide range.

Results

The results of the analog model for various temperature steps are shown in Fig. 2. The 222°K step corresponds to plunging the room temperature thermometer into boiling liquid nitrogen. The

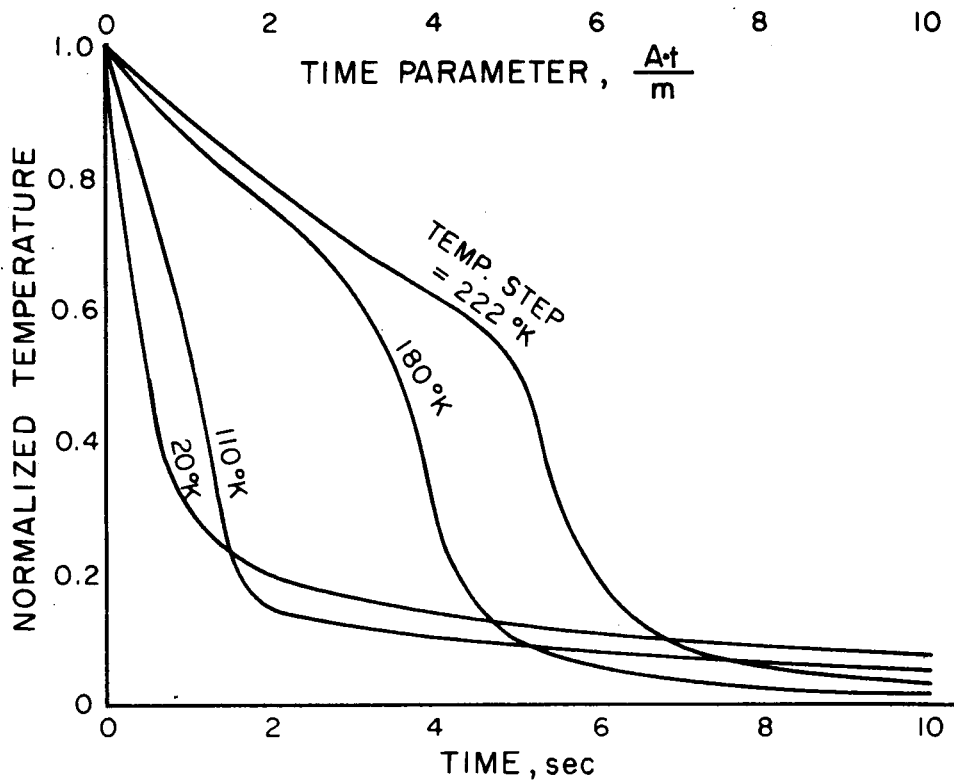


Fig. 2

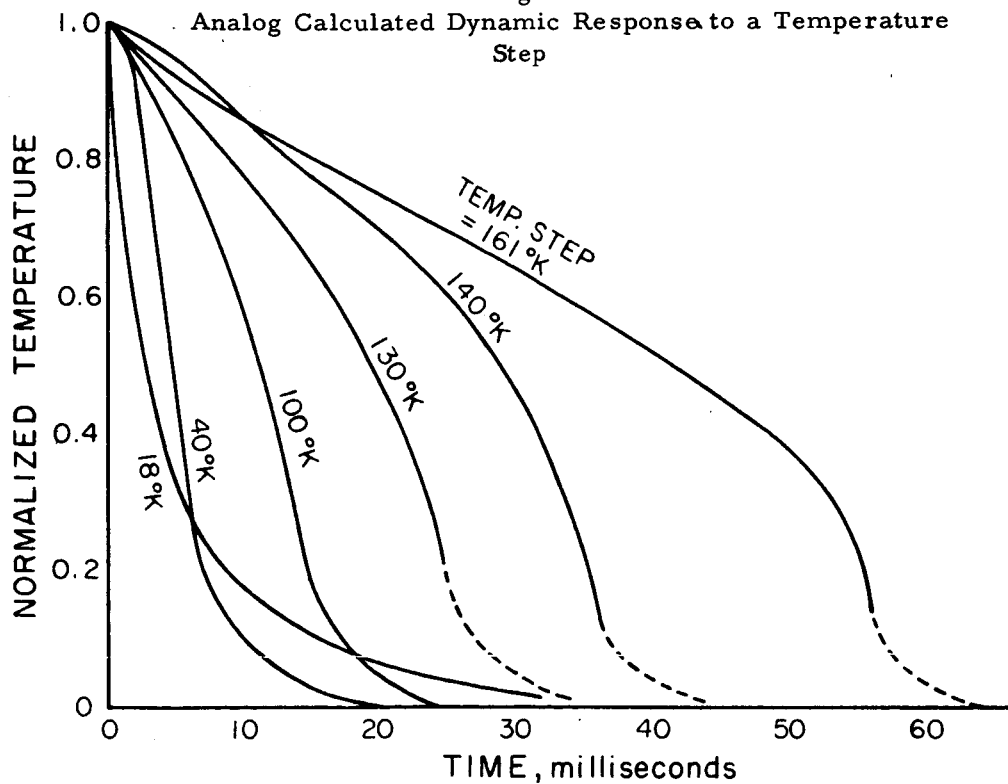


Fig. 3

Experimental Dynamic Response of a Cu-Cn Thermocouple to a Temperature Step

other temperatures correspond to various degrees of precooling. Experimental verification of the analog model is shown in Fig. 3. The same curve shapes are obtained; the difference in the time scale is due to the difference between the mass of the calculated and tested thermocouple junction. The experimental work is that of C. E. Miller [2]. Fig. 4 shows the effect of varying the parameter, $m C_p / A$.

As a comparison, experimental results taken for a multiple mass platinum resistance thermometer are shown in Fig. 5. This work was done by M. D. Bunch [3].

Discussion

The experimental curve for the thermocouple is similar in shape to the calculated curve, however, a slight departure occurs. This may be due to the lead wire conduction, the temperature dependency of the specific heat of the thermocouple junction or the difference between the realized h - T relationship and the one used in Table I. It is interesting to note that thermometers that have elements protected in probes, typically a platinum resistance thermometer, do not have the same characteristics response curve of the single mass thermometer.

It is thought that the pool boiling heat transfer coefficient, h , is the controlling mode of heat transfer for the simple thermocouple while the heat transfer into the platinum thermometer is more complex. The conduction across a layer of gas near the platinum wire probably controls the heat transfer rather than the pool boiling coefficient that occurs at the probe wall.

It is seen that the time for the thermometer to reach equilibrium temperature after a step temperature change is a strong function of the pool boiling coefficient, the thermometer geometry, and the thermometer characterization coefficient, $m C_p / A$. Since the

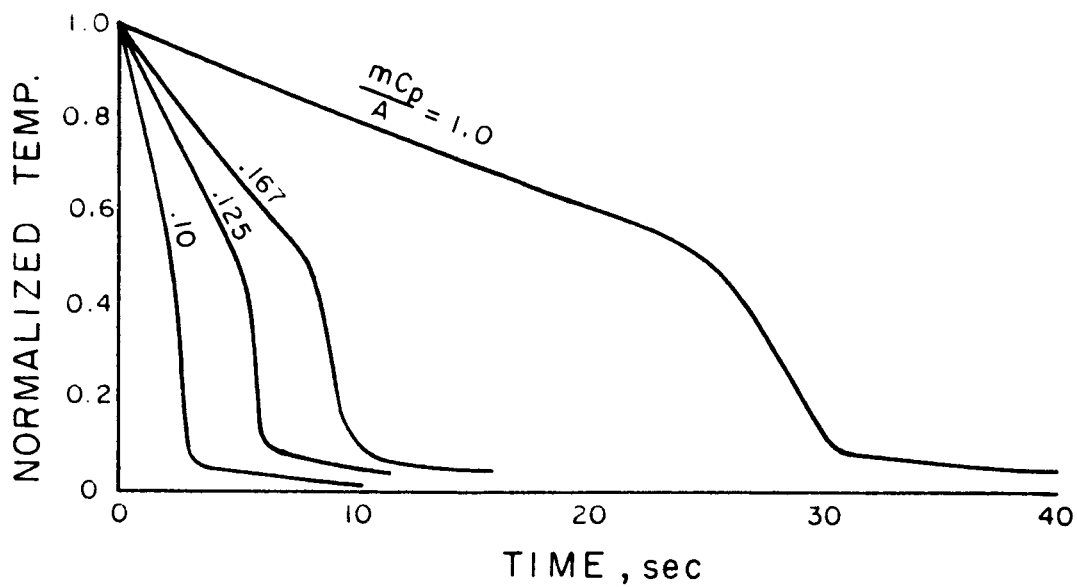


Fig. 4
Effect of Thermometer Characterization Parameter on Dynamic Response

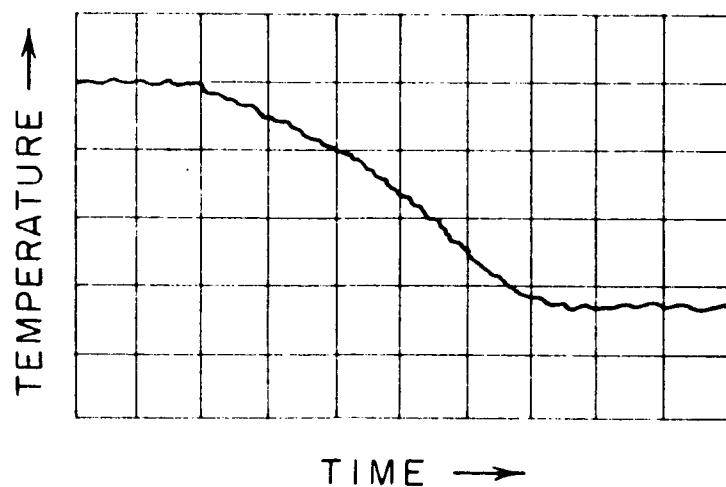


Fig. 5
Dynamic Response of a Typical Platinum Resistance Thermometer to a Temperature Step

response time is a function of the pool boiling coefficient, it is also a function of temperature. Thus the three different techniques mentioned in the introduction will give three different time constants for the same thermometer.

Conclusions

The analog computer is a useful tool for modeling the response time of temperature transducers. The single mass thermometer has been successfully modeled on the computer and a model of a multi-mass thermometer could be attempted.

The time constant as defined by the ISA actually depends on the temperature step used for both theoretical and experimental thermocouples. Thus, the time constant reported for thermometers built by different manufacturers using different testing techniques for cryogenic thermometers are not comparable. Therefore, it appears that time constants as reported by manufacturers using a variety of measurement techniques is of little utility.

References

- [1] "Nucleate and Film Pool Boiling Design Correlations for O_2 , N_2 , H_2 , and He" E. G. Brentari and R. V. Smith, 1964
Cryogenic Engineering Conference paper P-1.
- [2] NBS Report 7279.
- [3] NBS Report 8213.

2.2 Pressure

Considerable thought has been given to the problem of designing a pressure transducer for cryogenic service. The following describes this problem:

Design Problems of Isostatic Pressure Transducers for Cryogenic Service

Introduction

It has been shown [1] that the problem with cryogenic pressure transducers is due to the change in the properties of materials in the various transduction components. The change in the modulus of elasticity of the force summing element, either a Bourdon tube, a diaphragm, or a bellows, is the main cause of sensitivity shifts at cryogenic temperatures. The temperature dependency of the expansivity of the metals comprising the various linkage elements is the prime contributor to zero shifts. These effects can be temperature compensated over a range of 300 or 400°F in the order of 2 to 5 percent; however, this requires uniform temperature conditions throughout the pressure transducer. Temperature gradient effects can cause errors in excess of 100 percent of full scale. In order to avoid these temperature effects, it is thought to be useful to design a pressure transducer without the usual diaphragm and linkage element. Such a pressure transducer may be made by an isostatic design. The object of this note is to document some of the foreseen design problems in this approach.

Analysis

The electrical output of a pressure transducer may be considered as a function of pressure, temperature, strain, acceleration, and other inputs. For the purpose of this work let us consider the electrical output as a function of pressure and its major interference input, temperature. Writing the total differential of this relationship;

$$de_o = \left(\frac{\partial e_o}{\partial p} \right)_T dp + \left(\frac{\partial e_o}{\partial T} \right) dT \quad (1)$$

The first coefficient of equation (1) is the sensitivity of the pressure transducer, while the second coefficient is the zero shift coefficient. In an ideal pressure transducer the sensitivity remains constant throughout the temperature range while the zero shift coefficient is zero. In practice ideality is never achieved. A possible solution is to make the dT term of equation (1) be zero by controlling the environment temperature at a constant level. Under this condition the temperature dependency of the first coefficient of equation (1) the sensitivity, does not matter. The problem with this approach is that a special environmental chamber must be built for the pressure transducer, or a long tube must be used to remove the pressure transducer from the cryogenic environment. Pressure transducers environmental chambers have been described in [1, 2].

An isostatic pressure transducer may be built from a material whose electric resistivity is a sufficiently strong function of pressure. The electrical resistivity of most material is a function of pressure, temperature and strain. Now write the total differential for this relationship:

$$dR = \left(\frac{\partial R}{\partial p} \right)_{T, \epsilon} dp + \left(\frac{\partial R}{\partial T} \right)_{P, \epsilon} dt + \left(\frac{\partial R}{\partial \epsilon} \right)_{T, P} d\epsilon \quad (2)$$

Dividing both sides of equation [2] by R , the results are as follows:

$$\frac{dR}{R} = \frac{1}{R} \left(\frac{\partial R}{\partial p} \right)_{T, \epsilon} dp + \frac{1}{R} \left(\frac{\partial R}{\partial T} \right)_{P, \epsilon} dt + \frac{1}{R} \left(\frac{\partial R}{\partial \epsilon} \right)_{T, P} d\epsilon \quad (3)$$

Equation (3) is an expression for the unit change of resistance of a material in terms of the resistance-pressure coefficient, the resistance-temperature coefficient, and resistance-strain coefficient. The last

coefficient, the resistance strain coefficient, is usually written as a gage factor. For the rest of this work, we will not consider strain. We will assume that the material is mounted in a strain free manner and that the third term of equation (3) will thus drop out. The first coefficient is here called the isostatic coefficient. This coefficient defines the resistance change in a material due to a uniformly applied (isostatic) pressure. The term piezoresistance coefficient has not been used as it does not adequately define the difference between the resistance-pressure coefficient and the resistance-strain coefficient. In some commercial pressure transducers now on the market, pressure is applied to an element by mechanical strain and the resulting instrument is called a piezoresistive transducer. In this work the term isostatic pressure transducers is reserved for those whose resistance and thus electrical output change is caused only by the direct application of a pressurizing fluid.

With the strain term removed, equation (3) looks like equation (1). Thus the same problem of differentiating between temperature and pressure effects will occur with the isostatic pressure transducer. Usually the temperature coefficient is considerably larger than the isostatic coefficient, therefore this approach does not look initially attractive. Again, an environmental chamber might be used to eliminate the temperature effects. However, the use of resistive elements allows its application in a subtractive electrical network, such as wheatstone bridge. If all resistive elements in this bridge do not have the same isostatic coefficient and the same temperature coefficient proper operation will be achieved only in a uniform temperature environment. In order to attain an infinite common mode rejection ratio for this circuit, the temperature of the various detective elements and their pressure-temperature coefficients must be identical. Therefore, it is necessary to mount all the resistive elements in thermal contact

with a copper block or other high thermal conductivity material. Thus the design for an isostatic pressure transducer becomes one primarily of heat transfer considerations and of matching the pressure-resistance and temperature-resistance coefficients in a bridge circuit.

The equation for the output of a Wheatstone bridge is:

$$e_o = \frac{n e_i \Delta R}{4R} \quad (4)$$

where

- n = number of active bridge arms
- e_i = excitation voltage
- R = resistance
- ΔR = change in resistance

Now writing the isostatic coefficient in terms of increments and substituting into equation (4) results in:

$$e_o = \frac{n e_i \alpha \Delta v}{4} \quad (5)$$

where α is the isostatic coefficient $\frac{1}{R} \frac{\Delta R}{\Delta p}$. Two active arms would normally be used for absolute and gage measurements, while four active arms would be used for differential measurements.

Table I is a list of average isostatic coefficients for several materials.

The insertion of the values for the isostatic coefficients from Table I into equation (5) allows the calculation of bridge output. Excitation voltages of up to 15 volts have been successfully used with carbon composition resistors in such a bridge. Voltages beyond this have resulted in bridge self heating. The experimental bridge experienced some zero shift since all resistors did not have identical

Table I

Average Pressure-Resistance Coefficients of Materials
Near Room Temperature
[3, 4]

<u>Material</u>	<u>Pressure Resistance Coefficient</u> <u>psi⁻¹</u>
Aluminum	-2.8×10^{-7}
Antimony	$+7.8 \times 10^{-7}$
Bismuth	$+1.4 \times 10^{-6}$
Cadmium	-6.4×10^{-7}
Carbon Composition Resistors	-1.2×10^{-5}
Copper	-1.4×10^{-7}
Gallium Antimonide	-7.0×10^{-6}
Germanium Telluride	$+2.2 \times 10^{-6}$
Iron	-1.6×10^{-7}
Lithium	$+5.4 \times 10^{-7}$
Mangonin	$+1.6 \times 10^{-7}$
Mercury	-1.4×10^{-6}
Platinum	-1.4×10^{-7}
Rubidium	-4.2×10^{-6}
Silver	-2.3×10^{-7}
Sodium	-2.8×10^{-6}
Strontium	$+2.8 \times 10^{-6}$
Ytterbium	-3.2×10^{-5}

temperature-resistance coefficients. This zero shift effect might be somewhat reduced by an adequate heat transfer design in the sensing element mount. By allowing the energy to flow out of the sensing elements into a copper block, temperature rise of the sensing element will be reduced. However, for the purpose of estimating bridge outputs, 10 or 15 volts may be used as a bridge excitation. The most promising materials from Table I are carbon as in the form of carbon composition resistors and ytterbium wire. Using these materials in a two active arm bridge arrangement with an excitation voltage of 10 to 15 volts will result in a pressure transducer sensitivity in the order of 100 to 200 microvolts per psi. In other words, a bridge output of ten millivolts could be expected for a pressure measurement of a hundred psi. This output is in the same order of magnitude as being currently attained by strain gage bridge type pressure transducers; however, increasing the pressure range and excitation voltage allows a considerable improvement over the strain gage bridge type pressure transducers.

Examination of equation (5) shows that the bridge output is the function of the isostatic coefficient. If this coefficient changes with temperature the bridge sensitivity can also be expected to be a function of temperature. Therefore it behooves us to examine the isostatic coefficient as a function of temperature. Fortunately the isostatic coefficient is reasonably independent of temperature over a wide range; however, near liquid nitrogen temperature this coefficient starts to become a stronger function. A simple experiment with a carbon composition resistor has shown that the isostatic coefficient increases by approximately 5 to 10 percent at liquid nitrogen temperature. Therefore sensitivity temperature compensation will be required in the isostatic pressure transducer. This might be accomplished by mounting the temperature compensating element directly to the same block of copper that the pressure sensing elements are mounted. This is done to avoid thermal

gradients between the sensing and temperature compensating elements.

Summary

The analysis of isostatic pressure transducers has shown that adequate voltage output may be attained in a bridge arrangement, that identical isostatic and temperature coefficients must be used in the pressure sensing elements in all arms of the bridge, that temperature gradients between the sensing elements of all arms of the bridge must be avoided, in that sensitivity compensation will be required for extreme temperature spans of operation. Thus the design of an isostatic pressure transducer is primarily one of matching the sensing elements so that there is little if any temperature gradients between them. This design will be difficult to execute; however, it is felt that it is more profitable than the usual pressure transducer design using various diaphragm and linkage elements.

References

- [1] "Temperature Effects on Pressure Transducers", J. W. Dean and T. M. Flynn (in press).
- [2] Sixteenth Progress Report to NASA, NBS Report 8728.
- [3] P. W. Bridgman, Proc. Natl. Acoust. Sci. U.S., 3, 10, (1917).
- [4] "Effects of Pressure on the Electrical Resistance of Certain Metals", H. D. Stromberg, D. R. Stephens, J. Phys. Chem. Solids, Pergamon Press 1964, Vol. 25, pp 1015.

2.3 Liquid Level

The liquid level program has been completed.

2.4 Flow

An apparatus has been designed and tested for the purpose of correlating its design concept with those of a conventional water flow calibration facility. The following describes and presents the initial correlation.

Rotating Boom Flow Measurement Apparatus

The flowmeter calibration facilities for cryogenic liquids which are now available are large, expensive installations operating on a gravimetric principle. Even so, only small flowmeters - those with a diameter of one or two inches - may be calibrated on short duration runs at a high cost. A typical cost of a 15 point calibration is \$7,000. With this in mind, it was deemed desirable to develop an apparatus which would allow the transfer of a calibration of a standard flowmeter to an uncalibrated meter at a much lower initial investment and operating cost.

For a flowmeter test, it is necessary merely to establish a relative velocity between the flowmeter and the fluid. Conventionally, this relative velocity is achieved by moving the fluid through a stationary flowmeter. An unconventional approach is that of moving the flowmeter through the liquid. This concept has been tested by constructing a simple apparatus operating with water. This apparatus is simple in construction; employing an annular shaped fluid reservoir, a flowmeter mounted in a streamlined housing, and a variable speed drive mechanism (see Fig. 1). This apparatus does not require large-sized fluid tanks, pumps or gas drive systems, valves, transfer lines, and tank volume gaging systems or tank weighing systems such as is found in conventional calibration facilities.

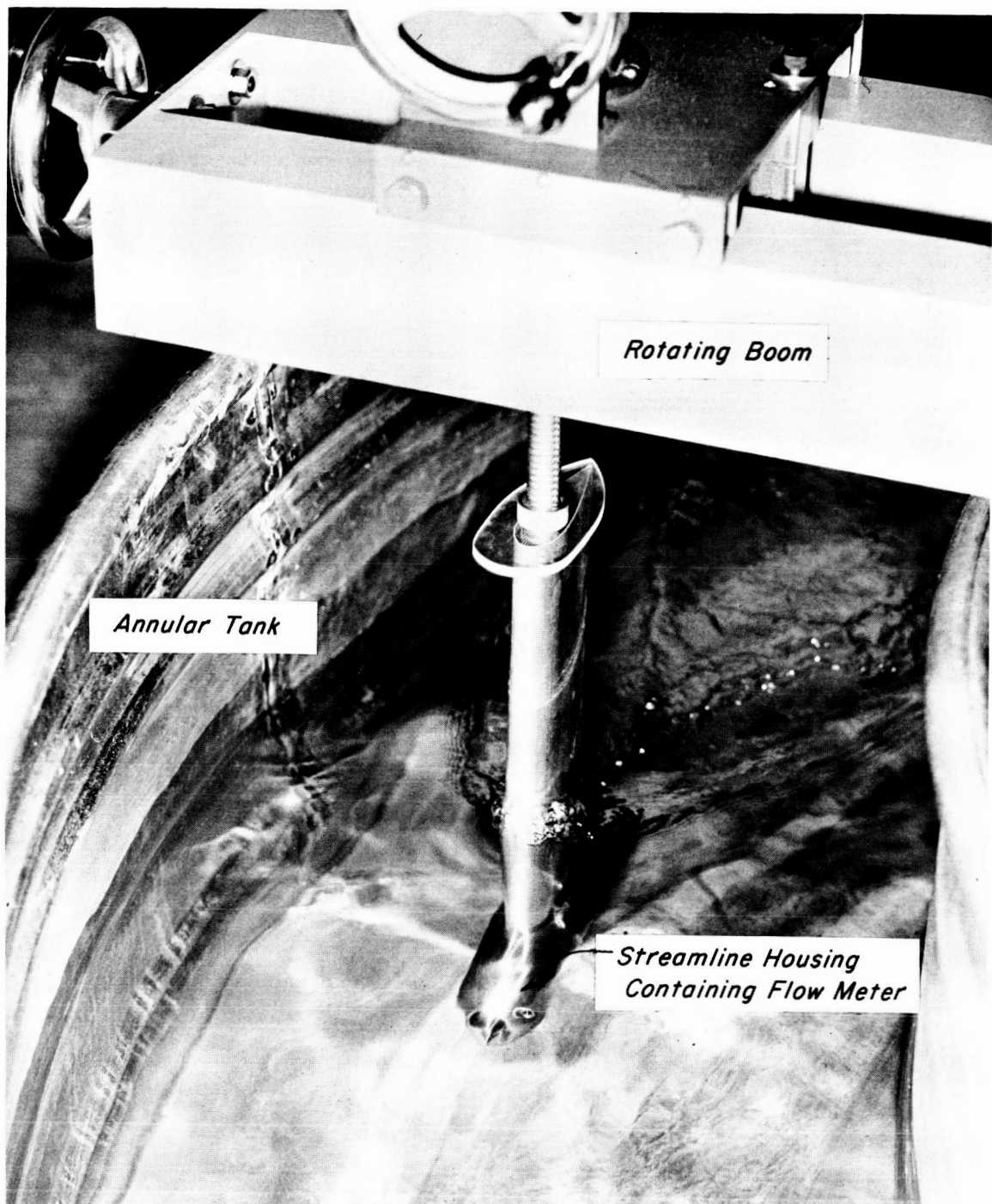


Fig. 1
Flowmeter Test Apparatus

Calibration transfer is established by placing two meters - the standard and the uncalibrated meter - end to end so that the flow rate is identical in both meters and recording the meter outputs for the desired flow rate. The flow rate is controlled by adjusting the speed of the boom.

It is interesting to consider this apparatus from a simple analytical viewpoint. Accordingly, for our test, we borrowed a turbine type flowmeter from NASA, MSFC, that had been calibrated on their conventional flow facility. The NASA calibration is shown in Fig. 2 along with a simple calculated flow rate from knowing the boom velocity relative to the tank and the flowmeter cross sectional area. As expected, the calculated flow is less than the calibration due to the fact that drag of the streamline housing imparts a velocity to the fluid. The interesting result is that the slopes of the experimental and calculated calibration curves differ by a constant multiplicative factor. The difference is shown by the error insert on Fig. 2. This means that the system could be calibrated with a primary standard once, or periodically, and the factor determined. Between system calibrations, the standard could be safely stored and meter calibrations determined by a simple calculation.

If the constant factor could be reliably predicted analytically, then the calibration system usefulness might be enhanced and extended beyond the current capability of gravimetric calibration systems. This possibility is currently being explored.

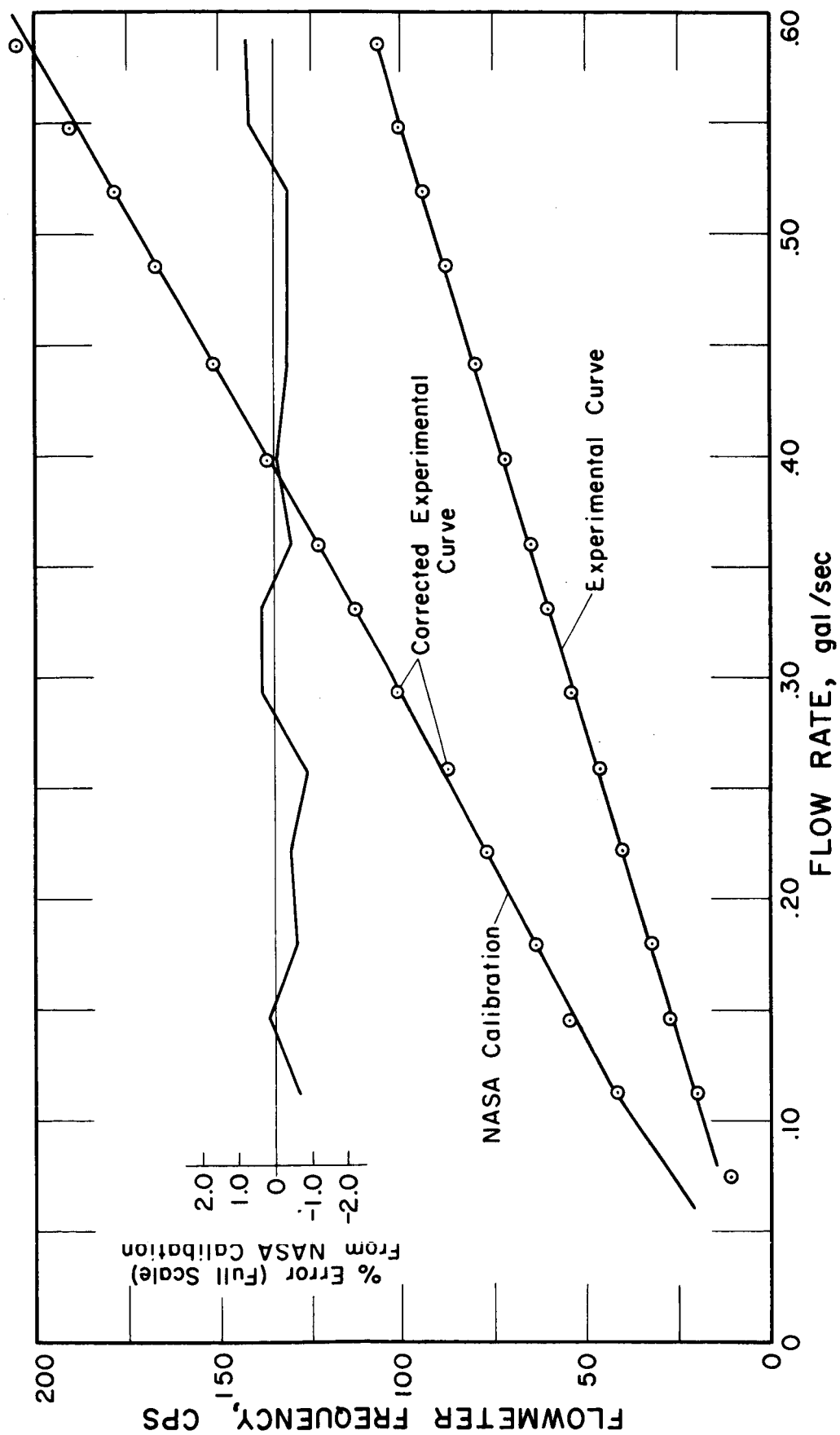


Fig. 2
Results of Flowmeter Calibration

3. Consultation and Advisory Services

Consultation and advisory services in the general field of cryogenic engineering has continued in several NASA program areas: Centaur (funded separately), NERVA, and M-1. Each area is discussed separately in the following pages.

3.1 Centaur Program - R. W. Arnett

Discussions via telephone contact with NASA-Lewis Research Center have been frequent during this reporting period. Trips have been made to technical meetings at Colorado Springs, Colorado and Palo Alto, California. Attendance at these meetings was for the purpose of maintaining an awareness of current developments in the cryogenic propulsion field. The meeting in Palo Alto, held at the Lockheed Missile and Space Co. Research Laboratories was particularly informative.

3.1.1 Stratification and Pressurization

Programming of the equations developed in the interim report entitled "A Method for Analyzing Thermal Stratification and Self Pressurization of a Fluid Container" has progressed to the debugging stage and the program should be operational in the near future.

3.1.2 Flight Data Analysis

Plans are made for developing a method of rapid flight data analysis using analog to digital reduction of the initial flight data. This capability is planned to be ready prior to the AC-7 launch date for a checkout run.

3.1.3 General Dynamics/Convair Testing Program

Plans are made and equipment checkout is under way for implementing tests on the liquid-vapor sensors and the temperature sensors to be used as part of the interior instrumentation of Flight AC-8. A trip to San Diego is planned in mid-July to discuss operating procedures for these sensors.

3.2 NERVA Program - Alan F. Schmidt

Information pertaining to the design and use of Joy-Collins type concentric ribbon-packed heat exchangers was provided SNPO-C early in this reporting period, together with transport property data for helium and nitrogen.

Further discussions were held on the general topic of para-ortho hydrogen property differences; two reports on this subject have been completed during this quarter because of the interest expressed by SNPO-C:

1. "Temperature Differences in Supercritical Hydrogen Flow Due to Variations of the Para-Ortho Concentrations, by Brentari, Jones, and Smith, NBS-CD Laboratory Note 65-9 (April 21, 1965).
2. "A Compilation of the Property Differences of Ortho and Para Hydrogen or mixtures of Ortho and Para Hydrogen", by Hust and Stewart, NBS Report 8812 (May 20, 1965).

Further work is in progress in this area and will be reported at a later date.

Information was also provided concerning the design and system characteristics of analyzers for the determination of ortho-para hydrogen concentrations. A number of these instruments have been

built, modified, and used in the Boulder Laboratory over the period of its existence in catalyst development and other research programs.

3.3 M-1 Engine Program - Alan F. Schmidt

On April 21-23, 1965, a trip was made to Aerojet-General Corporation - Liquid Rocket Operations, Sacramento, California, at the request of the M-1 Project Office to review initial E-Area liquid hydrogen charging and flow operations. Informal discussions were held with various M-1 program and facility managers and test area personnel concerning diverse program topics and problems.

Communication was maintained with AGC-LRO on the high pressure hydrogen gas receiver failures (see previous quarterly report for details of this business), and additional information was forwarded to the Test and Facility Planning Manager concerning hydrogen embrittlement of certain select steel construction materials.

Information was also requested by AGC concerning the precision of data available on the density of liquid oxygen (a current NBS program) and gaseous hydrogen; the oxygen material is being prepared, and the data on hydrogen were forwarded by mail.

4. The Compilation of Thermophysical Properties of Cryogenic Materials

R. B. Stewart and V. J. Johnson

The report on this activity is now being given in a composite report for all activities of the Cryogenic Data Center. The report is entitled "Second Quarterly Progress Report on Cryogenic Data Center Activities for the Period Ending June 30, 1965" and identified as NBS Report 8838. This report is being mailed to a distribution list compiled by the sponsors. Others who wish to receive it and future progress reports on the Cryogenic Data Center activities are invited to address their requests to: V. J. Johnson, Chief, Cryogenic Data Center, National Bureau of Standards, Boulder, Colorado.

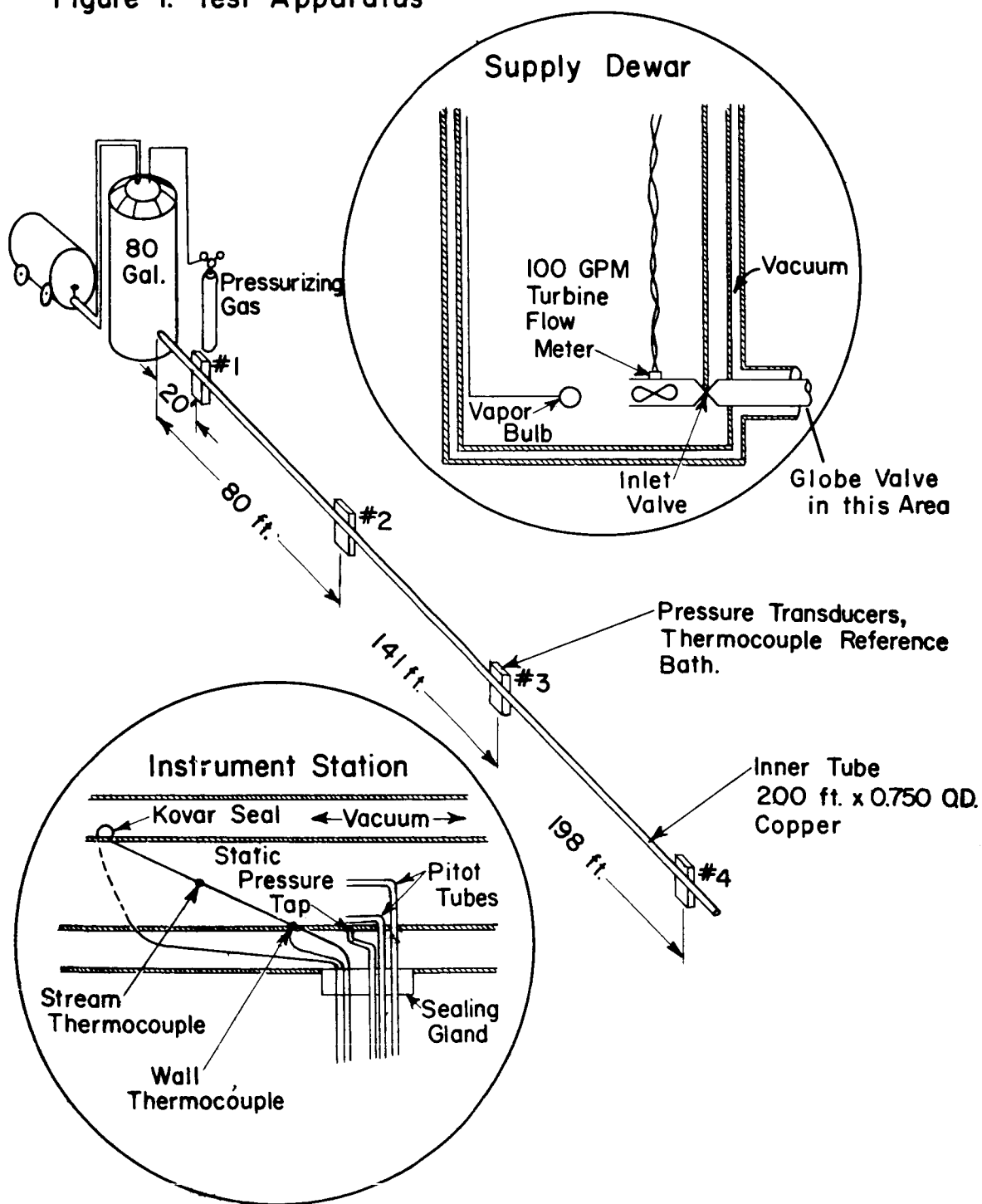
5. Cryogenic Flow Processes

5.1 Experimental

Work on the experimental phase of this project proceeded throughout this reporting period. As was mentioned in the last progress report the globe valve was removed from the system leaving the ball valve for control as in the apparatus for the first series of tests. With this arrangement it was possible to reproduce the pressure surges, at the higher driving pressures, that were obtained with this configuration in the earlier phases of this project. It was necessary to partially precool the line in order to have these high surges occur, however. The valve location and instrumentation stations are shown schematically in Fig. 1.

Fig. 2 shows some of the pressure surges obtained thus far with liquid hydrogen. The results shown are for subcooled hydrogen, i. e., the liquid was saturated at atmospheric pressure (approximately 12 psia) and rapidly pressurized to the indicated driving pressure just before the valve was opened. No satisfactory explanation of the large scatter at 100 psig driving pressure has been found. The number adjacent to each point in Fig. 2 is the temperature, in degrees Kelvin, of the line at a point 20 feet from the supply dewar at the start of the test. There are points on Fig. 2 represented by the triangles that appear to lie in two different areas. The upper two points were obtained by precooling the line just before the start of the test. This appears to indicate that line temperature controls the peak line pressure obtained, but perhaps only at higher driving pressures. At 50 psig driving pressure, however, there was very little effect on line pressure as the line temperature was varied over a wide range. Further testing and analytical work will be required to determine the effect of precooling the line.

Figure 1. Test Apparatus



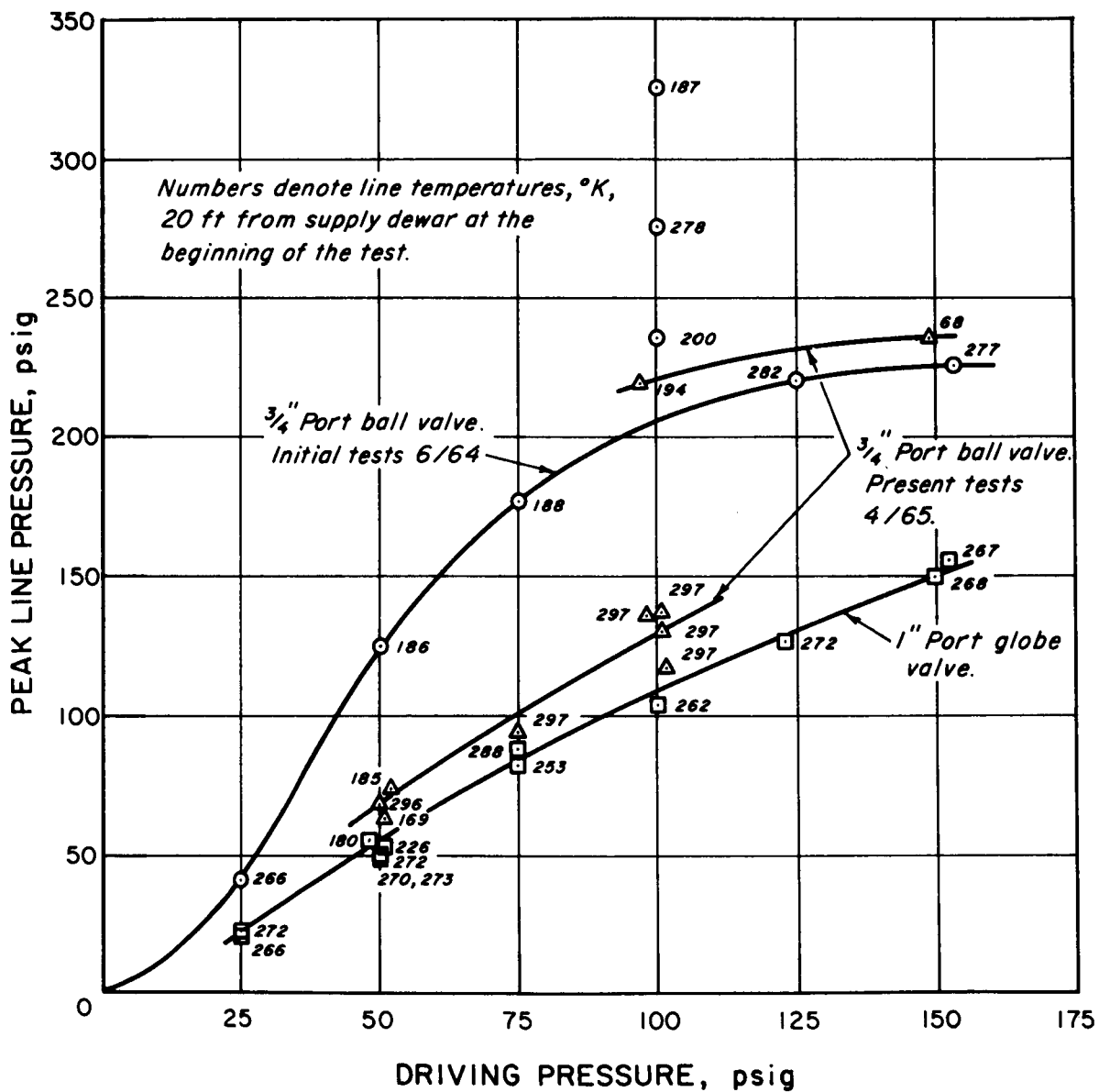


Fig. 2 Peak Line Pressure as a Function of Driving Pressure for Subcooled Liquid Hydrogen (Hydrogen Temperature Approximately 19-1/2°K)

The bottom line in Fig. 2 shows the results of tests in which the control valve was the one-inch-port-globe-valve. With this valve there was little pressure surging in the line and, in fact, the results of the tests in which the hydrogen was subcooled yielded line pressures only slightly higher than those produced where the hydrogen was saturated at the indicated driving pressure. In the runs where the liquid was saturated at the driving pressure, there was no significant pressure surging with either valve arrangement.

It was stated in the last progress report that experimental testing on two-phase choking using nitrogen and hydrogen would start this reporting period. Unfortunately this testing did not start because the flowmeter was damaged and it was necessary to send it to the factory for repair. In the interim, a smaller capacity meter has been sent to NASA-Lewis for calibration. It will be possible to start the choking experiments with this meter and it is planned to do so just as soon as the meter is returned.

In the absence of a flowmeter, it was decided to continue investigating peak line pressure. The different surging behavior between the globe and the ball valves indicated that line entrance effects were significant and it was decided to investigate these further. Twisted tape, elbows, and orifices were placed near the entrance and their effect on pressure surging was observed. Most of the work was done with liquid nitrogen, primarily because it produces the highest pressures which appear to persist even when the hydrogen does not.

The twisted tape consisted of a strip of brass one diameter wide, 8 inches long, and 0.011 inches thick, twisted approximately 180°. The tape ends were hard soldered to the inside of the tube. With a driving pressure of 75 psig over subcooled liquid nitrogen, line pressure exceeded 350 psig beyond station 3 which was 141 feet

from the supply dewar. The resulting back flow tore loose the tape around the solder joint and blew parts of it back through the valve, flowmeter, and screen.

Table 1 lists the various restrictions used and peak line pressure that resulted.

Table 1

<u>Restriction</u>	<u>Fluid</u>	<u>Driving Pressure psig</u>	<u>Peak Line Pressure psig</u>
Wire Crisscross	LN ₂	25	88
		50	103 to > 350
Eight 90° elbows	LN ₂	25	83
		50	122 - 187
		75	235
1/2" orifice	LN ₂	25	88
		50	110
		75	125 to > 350
3/8" orifice	LN ₂	25	67
		50	87
		75	113 - 130
		100	153
1/4" orifice	LN ₂	25	40
		50	93 - 110
		75	137 - 144
		100	138 - 140
1/4" orifice	LH ₂	25	32
		50	72
		100	100 - 112
		150	152 - 153

The wide variations in line pressure experienced with liquid nitrogen makes any general statement concerning the results very risky. It should be noted, however, that the 3/8" and 1/4" orifices eliminated the very high pressure surges.

The peak line pressures obtained with the 1/4" orifice when liquid hydrogen was the cryogen were very similar to those obtained with the globe valve, that is, only small surges.

Since these tests were slanted toward line pressure phenomena they were of short duration. Only one test was run long enough to cool-down the entire transfer line and that one was a 150 psig driving pressure liquid hydrogen test. The cooldown time for this test was not significantly different than the times obtained when there was no restriction in the line. The pressure distribution in the line after cooldown was at a lower level with the orifice than it was with the ball or globe valve alone, however.

Experimental work on the 200 ft. long transfer line has been stopped and the modifications to the equipment necessary for the two-phase choking experiments were underway at the close of the reporting period. The choking experiments will be started early in the next period.

"Comparison of Mass-Limiting Two-Phase Flow in a Straight Tube and in a Nozzle", by D. K. Edmonds and R. V. Smith, a technical paper presenting the data obtained from the Refrigerant -11 experiments were presented in Exeter, England, at the symposium on two-phase flow. Twenty-five copies have been sent to the NASA Library. Copies can be provided upon request from the authors.

5.2 Analytical

A section of the manuscript on boiling mentioned in the last two reports has been accepted for presentation at the 1965 Cryogenic Engineering Conference to be held at Rice University, Houston, Texas, August 23 - 25, 1965. The paper by Giarratano and Smith, is entitled "Comparative Study of Forced Convection Boiling Heat Transfer Correlations for Cryogenic Fluids." Copies will follow when returned from printing.

Lab Note 65-9 by Brentari, Jones, and Smith dated April 21, 1965, contains the information generated in the ortho-para study mentioned in the last report. Copies of this will be supplied upon request.

NBS Technical Note No. 317 was prepared by Brentari, Giarratano, and Smith entitled "Boiling Heat Transfer for Oxygen, Nitrogen, Hydrogen, and Helium". This note is in the final stages of publication. Chapter 3 of this note which is essentially the same as the Cryogenic Engineering paper was partially supported by Contract R-45.

Work on the mathematical cooldown model was resumed this period with programing being done on two models. One, the two-phase model, was a new endeavor and no results had been obtained at the close of the period. The other model is the one developed by Steward at this laboratory and the work done consisted of changes to the original program in an effort to better predict the peak line pressures and entrance effects obtained with liquid hydrogen. Work on both of these models will continue next reporting period.